PROJECTION EXPOSURE APPARATUS, AND DEVICE MANUFACTURING METHOD USING THE SAME

FIELD OF THE INVENTION AND RELATED ART

This invention relates to a projection exposure apparatus and a device manufacturing method using the same. For example, the invention is suitably applicable to a projection exposure apparatus or a scan type exposure apparatus to be used in a lithographic process, among device manufacturing processes for production of semiconductor devices such as IC or LSI, image pickup devices such as CCD, display devices such as a liquid crystal panel, or magnetic heads, for example, particularly in relation to projection of a pattern of a first object such as a reticle onto a second object such as a wafer through a projection optical system.

As regards a microprocessing technology for semiconductor devices such as IC or LSI, many proposals have been made on a reduction projection exposure apparatus (stepper) or a scan type projection exposure apparatus, for forming an image of a circuit pattern of a mask or reticle upon a photosensitive substrate through a projection optical system (projection lens) and for exposing the photosensitive substrate in accordance with a step-and-repeat method or a step-and-scan method.

In these exposure apparatuses, a pattern of a reticle must be transferred onto a wafer accurately in accordance with a predetermined magnification (reduction ratio). To this end, it is important to use a projection lens (projection optical system) having a good performance and small aberrations. Particularly, in order to meet recent requirements of further miniaturization of a semiconductor device, in many cases a pattern which is beyond the normal imaging performance of a projection optical system has to be transferred to a wafer. Thus, the aberration of a projection optical system becomes very influential to the pattern to be transferred. On the other hand, for the projection lens, enlargement of an exposure area as well as enlargement of its numerical aperture (NA) are desired, which are not convenient for aberration correction.

In these circumstances, it is desired to perform measurement of the imaging performance of a projection lens, particularly, wavefront aberration thereof, in a state that the projection lens is being mounted on an exposure apparatus, that is, a state that it is used for a practical exposure process.

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An example of measurement methods for wavefront aberration of a projection lens is a phase restoration method. This method has bee used in the field of electron microscopes or astronomical

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telescopes having large aberrations, for improvement of the resolution. In accordance with this phase restoration method, a phase distribution of an image is detected on the basis of image intensity distributions at plural positions such as image plane, pupil plane, and defocus position, for example. From the detected phase distribution, a wavefront aberration of an optical system is calculated.

In this phase restoration method, an actually measured intensity distribution of an image on an image plane is used and, after an arbitrary phase is applied, Fourier transform is made thereto to detect a complex amplitude distribution upon a pupil plane. Subsequently, while keeping a phase component of the thus detected complex amplitude distribution, only an absolute value corresponding to an intensity component thereof is replaced by a value (root square of the intensity at the pupil plane) corresponding to the actually measured value. The result is then taken as a fresh complex amplitude distribution, and inverse Fourier transform is made thereto, to determine a complex amplitude distribution upon an image plane. Again, while keeping its phase component, the intensity is replaced by an actually measured value.

By repeating the above-described calculations, complex amplitude distributions on the image plane and the pupil plane are calculated and,

from the phase distribution of the complex amplitude distribution at the pupil plane, the wavefront aberration of the projection lens is detected. The phase restoration method will be described later in more detail, in conjunction with preferred embodiments of the present invention.

Where a wavefront aberration of a projection lens is to be calculated in accordance with the phase restoration method, idealistically it is necessary to measure an intensity distribution of an image under a condition of coherent illumination ($\sigma=0$). If the value σ (that is, a ratio of the numerical aperture of an illumination system to the numerical aperture of the projection lens) becomes larger, the calculated wavefront aberration contains a larger error. For example, if the wavefront aberration should be calculated with a precision of about 0.01λ, a relation $\sigma\leq0.1$ is required. Even though the precision is lowered to about 0.03λ, a relation $\sigma\leq0.2$ has to be satisfied. On the other hand, when a pattern of a reticle is to be photoprinted on a wafer, usually the reticle is illuminated under a partially coherent illumination condition. Thus, normally, an illumination system of an exposure apparatus has σ which is in a range of about $0.2<\sigma<0.9$. No illumination system as providing $\sigma\leq0.2$ is loaded. Further, many illumination systems for an exposure

apparatus are equipped with an incoherency-transforming mechanism.

For these reasons, when a wavefront aberration of a projection lens is to be detected in accordance with the phase restoration method while using an illumination optical system for a practical exposure process as it is, there is a problem in respect to the precision.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a projection exposure apparatus and/or a device manufacturing method using the same, by which a wavefront aberration of a projection optical system (projection lens) for projecting a pattern of a mask onto a wafer can be measured very precisely and by which production of a large integration device can be facilitated.

These and other objects, features and advantages of the present invention will become more apparent upon a consideration of the following description of the preferred embodiments of the present invention taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic view of a main

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portion of a projection exposure apparatus according to a first embodiment of the present invention.

Figure 2 is a schematic view of an exposure illumination system in the apparatus of Figure 1.

Figure 3 illustrates a first algorithm of a phase restoration method, according to the present invention.

Figure 4 illustrates a second algorithm of a phase restoration method, according to the present invention.

Figure 5 is a schematic view of a main portion of a projection exposure apparatus according to a second embodiment of the present invention.

Figure 6 is a schematic view of a main portion of a projection exposure apparatus according to a third embodiment of the present invention.

Figure 7 is a schematic view of a main portion of a projection exposure apparatus according to a fourth embodiment of the present invention.

Figure 8 is a schematic view of a main portion of a projection exposure apparatus according to a fifth or sixth embodiment of the present invention.

Figure 9 is a schematic view of a main portion of a projection exposure apparatus according to a seventh embodiment of the present invention.

Figure 10 is a schematic view of a main

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portion of a projection exposure apparatus according to an eighth embodiment of the present invention.

Figure 11 is a flow chart of device manufacturing processes according to an embodiment of the present invention.

Figure 12 is a flow chart for explaining details of a wafer process, in the procedure of the flow chart of Figure 11.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 is a schematic view of a main portion of a projection exposure apparatus according to a first embodiment of the present invention, wherein a pattern (transfer pattern) of a reticle (first object) 2 is to be projected through a projection lens 1 onto a wafer (second object) 3. As compared with a conventional exposure apparatus having a wavefront calculating mechanism based on a phase restoration method, in the apparatus of this embodiment there is a demountably mountable coherency-transforming optical system 16 being added to an exposure illumination system 13.

In the phase restoration method for detecting a wavefront aberration of the projection lens 1 in this embodiment, first, an illumination light beam IL of exposure wavelength (printing wavelength) from an exposure illumination system (illumination optical

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system) 13 and passing through the incoherency-transforming optical system 16 illuminates a pattern (particular pattern) on the reticle 2 or on any other object. Then, an image of the particular pattern is formed (imaged) by the projection lens 1 upon a light intensity detecting means 8 which is mounted on a wafer stage 4. By using this intensity detecting means 8, an intensity distribution of the particular pattern image is measured. Subsequently, the wafer stage 4 is moved in an optical axis direction AX through a stage driving mechanism 5, such that, upon the light intensity detecting means 8 surface, the particular pattern image is defocused. The intensity distribution of the particular pattern image at that moment is measured. By using the results concerning the intensity distributions of these two pattern images, an information processing unit (wavefront aberration measuring means) 11 performs repeated calculations such as Fourier transform and inverse Fourier transform, for example, whereby the wavefront aberration of the projection lens 1 is calculated. It is to be noted here that the example shown in Figure 1 concerns measurement of a wavefront aberration on the optical axis of the projection optical system 1.

Figure 2 is a schematic view for explaining details of the exposure illumination system 13. In Figure 2, a light beam emitted from a light source 17

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such as a super high pressure Hg lamp or an excimer laser, for example, is transformed into illumination light of a desired shape, by means of a light shaping unit 18 including a beam expander or a cylindrical lens, for example. The light is then projected on an incoherency-transforming unit 19.

The incoherency-transformed light from the unit 19 is then received by an illumination state adjusting unit 20 including a zoom lens, by which the illumination σ value is adjusted. Subsequently, the light passes a lens array (fly's eye lens optical system) 21 having its lenses arrayed two-dimensionally, and then through an exit side stop 22, whereby the effective light source is determined. After this, the light is directed to a lens system 23. Thus, with the light from the lens system 23, the reticle 2 surface can be illuminated at a desired σ value determined through the incoherency-transforming optical system 16.

In this embodiment, since an excimer laser is used as the light source 17, the incoherency-transforming unit 19 is provided between the light shaping unit 18 and the illumination state adjusting unit 20. If an Hg lamp, for example, for emitting incoherent light is used as the light source, use of the incoherency-transforming unit 19 is unnecessary.

When a wavefront aberration of a projection

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lens 1 is to be calculated in accordance with the phase restoration method, idealistically it is necessary that the pattern of the reticle 2 is illuminated with coherent illumination ($\sigma=0$). If $0<\sigma$, there occurs an error in the calculation, and the error becomes larger with a larger σ.

On the other hand, usually a projection lens 1 of an exposure apparatus has a wavefront aberration of 0.1λ (λ is the wavelength). For evaluation of such wavefront aberration, the wavefront aberration should be calculated at least at an order not greater than 0.01λ. In order that the wavefront aberration is calculated by using the phase restoration method and with a precision not higher than 0.01λ, the pattern of the reticle has to be illuminated with light of $\sigma\leq0.1$. Further, also for qualitative evaluation of a relative change in wavefront aberration, for example, due to a change in environment caused by execution of an exposure process, a precision of an order of about 0.3λ is necessary. In that occasion, the reticle pattern should be illuminated with light of $\sigma\leq0.2$.

The exposure illumination system (first illumination system) 13 is generally arranged to perform illumination of the reticle 2 in a partially coherent state or an incoherent state (first illumination condition), for practical exposure process for printing a circuit pattern on the wafer 3.

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Thus, when the phase restoration method is executed only by use of the exposure illumination system 13, coherent illumination is not attainable and, therefore, the measurement has to be done while making σ of the exposure illumination system 13 smallest. However, even a smallest value σ as actually loaded in a semiconductor device manufacturing exposure apparatus is about 0.3. It is therefore very difficult to calculate the wavefront aberration by the phase restoration method, with a satisfactory precision.

In this embodiment, in consideration of the above, the coherency-transforming optical system 16 is inserted between the reticle 2 and the exposure illumination system 13, for measurement of the wavefront aberration, by which the illumination light being convergent spherical wavefronts, is transformed into light of parallel wavefronts. By this, the pattern of the reticle 2 can be illuminated through coherent illumination or approximately coherent illumination (second illumination condition). As a result, high-precision wavefront aberration calculation based on the phase restoration method can be accomplished.

While in this embodiment the coherency-transforming optical system 16 is added to the illumination optical system 13, the coherency-

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transform may be attained by removing a lens (e.g., the incoherency-transforming unit 19) of the illumination optical system 13 or by adding another optical system after the removal, for example.

In this embodiment as described hereinbefore, the illumination condition for the reticle is changed between an exposure process for printing a pattern of the reticle 2 on a wafer 3 and a process for calculating the wavefront aberration of the projection lens 1 based on the phase restoration method. More specifically, for the exposure process, the reticle 2 is illuminated with partially coherent light or incoherent light (first illumination condition). For the wavefront aberration calculation based on the phase restoration method, a pattern of the reticle is illuminated with coherent light or approximately coherent light ($\sigma \leq 0.2$, preferably, $\sigma \leq 0.1$) (second illumination condition), followed by measuring light intensity distributions upon a pupil plane and a defocus plane, and detecting the wavefront aberration of the projection lens 1.

Further, for the exposure process, the coherency-transforming optical system 16 is moved out of the light path, such that the reticle is illuminated in the partially coherent state (first illumination condition) while using the exposure illumination system 13 as it is. Then, for

measurement of the wavefront aberration based on the phase restoration method, a partial optical system is demounted from the exposure illumination system or, alternatively, the coherency-transforming optical system 16 is added thereto (of course, both may be done). By doing so, the wavefront aberration of the projection optical system can be calculated very precisely.

As an alternative, the light source may be changed so as to define best spatial coherency or best light quantity suitable for the exposure process and the phase restoration process, respectively, thereby to enable high precision calculation of the wavefront aberration of the projection optical system. As a further alternative, separate illumination optical systems (first and second optical systems) may be used for the exposure process and the phase restoration process, respectively, such that the reticle is illuminated in a partially coherent illumination state for the exposure process, while it is illuminated in a coherent or approximately coherent state for execution of measurement of the wavefront aberration of the projection lens based on the phase restoration method. This enable high precision calculation of the wavefront aberration of the projection optical system.

The second optical system may be an alignment optical system for performing alignment between a

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reticle and a wafer by use of light of exposure wavelength, or it may be a portion of such alignment optical system. If the illumination condition thereof is set to $0 \leq \sigma \leq 0.2$, the wavefront aberration can be calculated very precisely in accordance with the phase restoration method, without addition of any optical system in the exposure apparatus, or with minimum addition of an optical system. Alternatively, the illumination condition of the alignment system may be changed between the alignment measurement process and the wavefront aberration measurement process based on the phase restoration method, to assure best measurement states, respectively.

Figures 3 and 4 illustrate algorithms based on the phase restoration method, for measurement of a wavefront aberration of a projection lens, both usable in this embodiment.

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The phase restoration method method has bee used in the field of electron microscopes or astronomical telescopes having large aberrations, for improvement of the resolution. In accordance with this phase restoration method, a phase distribution of an image is detected on the basis of image intensity distributions at plural positions such as image plane, pupil plane, and defocus position, for example. From the detected phase distribution, a wavefront aberration of an optical system (projection lens) is

calculated.

The algorithm of phase restoration method shown in Figure 3 will be explained first. Initially, a measured intensity distribution of an image on an image plane is used and, after an arbitrary phase is applied thereto, Fourier transform is made thereto to detect a complex amplitude distribution upon a pupil plane. Subsequently, while keeping a phase component of the thus detected complex amplitude distribution, only an absolute value corresponding to an intensity component thereof is replaced by a value (root square of the intensity at the pupil plane) corresponding to the actually measured value. The result is then taken as a fresh complex amplitude distribution, and inverse Fourier transform is made thereto, to determine a complex amplitude distribution upon an image plane. Again, while keeping its phase component, the intensity is replaced by an actually measured value. By repeating the above-described calculations, complex amplitude distributions on the image plane and the pupil plane are calculated and, from the phase distribution of the complex amplitude distribution at the pupil plane, the wavefront aberration of the lens is detected.

Figure 4 illustrates an algorithm of phase restoration method in a case where measurement of an intensity distribution upon a pupil plane is difficult

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to accomplish, as in a photolithographic process. In the algorithm of Figure 4, between an image plane and a defocus plane across a pupil plane, transform and inverse transform are repeated, by which a complex amplitude distribution at the image plane and a complex amplitude distribution at the defocus plane are calculated. From the results, the phase distribution at the pupil, that is, the wavefront aberration of the projection lens is detected.

Figure 5 is a schematic view of a main portion of a projection exposure apparatus according to a second embodiment of the present invention. In Figure 5, elements corresponding to those shown in Figure 2 are denoted by like numerals.

In this embodiment, the illumination state adjusting unit 20 and the stop 22 of the exposure illumination system 13 as shown in Figure 2 are replaced by an illumination state adjusting unit 24 and a stop 25, between execution of an exposure process and execution of the phase restoration method. As shown in Figure 2, what determines the illumination condition for the exposure process is the combination of the illumination state adjusting unit 20 and the stop 22 inside the exposure illumination system 13. The illumination state adjusting unit 20 mainly comprises a zoom optical system which serves to change the size of an effective light source in accordance

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with the illumination condition for the exposure process.

Generally, the value σ in regard to the illumination condition for wafer exposure to print a pattern on the wafer is in a range of about 0.3 to 0.8. Thus, the zoom optical system may be one covering such range. In the phase restoration method, on the other hand, a reticle must be illuminated in an approximately coherent state wherein σ is not greater than 0.2, preferably, not greater than 0.1. For most convenient illumination with σ of 0.2 or less, the aperture 22 shown in Figure 2 may be narrowed to satisfy $\sigma \leq 0.2$. In that occasion, since at the illumination state adjusting unit 20 the light has an expansion as of about $\sigma = 0.3$, an eclipse may occur at the stop 22 portion and, as a result, the light quantity may decrease. Particularly, the light quantity may reduces if σ is not greater than 0.1. Thus, with the phase restoration method wherein the light intensity is to be measure, it may adversely influence the wavefront aberration calculation precision. While a zoom optical system that can cover a range of σ from 0.1 to 0.2 may be used, enlargement of the zoom ratio causes an increase in size and weight of the illumination state adjusting unit 20. Further, it becomes difficult to suppress non-uniformness of illuminance for all zoom lenses.

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In this embodiment, in consideration of the above, as shown in Figure 5, for execution of the measurement of the wavefront aberration of the projection lens on the basis of the phase restoration method, the illumination state adjusting unit inside the illumination optical system 18 is replaced by the illumination state adjusting unit 24 for the phase restoration method while, on the other hand, the stop is replaced by the stop 25 to change σ to be not greater than 0.2. More specifically, for the exposure process, a zoom optical system with which σ can change from about 0.3 to about 0.8 is used in the illumination state adjusting unit 20. For execution of the phase restoration method, the illumination state adjusting unit 24 for phase restoration method which which σ becomes not greater than 0.2 is used. In this manner, in both of the exposure process and phase restoration process, the reticle can be illuminated with best modes, respectively. As a result of this, the wavefront of the projection lens 1 can be measured very precisely.

Figure 6 is a schematic view of a main portion of a projection exposure apparatus according to a third embodiment of the present invention. In Figure 6, elements corresponding to those of Figure 2 are denoted by like numerals.

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In this embodiment, as shown in Figure 6,

fore execution of wavefront aberration measurement based on the phase restoration method, a demountable mirror 27 being movable out of the light path is inserted between a stop 22 and a lens unit 23. A second light source 26 emits light of the same wavelength as the exposure wavelength, so that, through the mirror 27 and the lens 23, a pattern on a reticle 2 is illuminated in coherent state or approximately coherent state. This differs from the first embodiment of Figure 2.

With the provision of the light source 26 for phase restoration, in addition to the exposure light source 17, the reticle 2 can be illuminated with a light quantity best suited for the phase restoration method. Thus, the wavefront aberration can be calculated very precisely. Further, while not shown in Figure 6, a lens or the like may be disposed between the second light source 26 and the mirror 27 or between the mirror 27 and the lens unit 23, for coherent illumination of the reticle.

Figure 7 is a schematic view of a main portion of a projection exposure apparatus according to a fourth embodiment of the present invention. In Figure 7, elements corresponding to those of Figure 1 are denoted by like numerals. Figure 7 concerns a case wherein a wavefront aberration out of the optical axis of the projection optical system 1 is to be

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detected.

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In this embodiment, as shown in Figure 7, a second optical system 14 is provided, in addition to the exposure illumination system 13. For detection of a wavefront aberration of the projection lens 1 on the basis of phase restoration method, the second optical system 14 is used to illuminate a pattern on the reticle 2. Also, for an exposure process, the second optical system 14 as well as the mirror 15 move in a direction of an arrow in Figure 7 so as not interfere with the exposure light. Namely, they are demountable out of the light path. Further, the illumination condition of the second illumination optical system 14 satisfies coherent illumination (σ=0) or approximately coherent illumination ($\sigma \leq 0.2$). Thus, the wavefront aberration of the projection lens 1 can be measured, under an idealistic condition for the phase restoration method.

In this embodiment, it is not at all necessary to change or modify the exposure illumination system 13. Thus, an optimum illumination state for the phase restoration method is accomplished in a very simple way. The light source for the second illumination optical system 14 may comprise the same light source as the exposure light source, or it may comprise a separate light source having the same wavelength as of the exposure light source.

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~~Figure 8 is a schematic view of a main portion of a projection exposure apparatus according to an fifth embodiment of the present invention. In Figure 8, elements corresponding to those of Figure 1 are denoted by like numerals.~~

In this embodiment, calculation of wavefront aberration of the projection lens 1 based on the phase restoration method can be done while using an alignment optical system for performing registration (alignment) between a reticle 2 and a wafer 3. As shown in Figure 8, the alignment optical system includes an objective lens 28, a beam splitter 29, a relay optical system 31, an illumination system relay optical system 33, a light source 34 and a sensor 30, for example. The light source 34 produces light of the same wavelength as of the exposure light, and it goes through the illumination system relay optical system 33 and the objective lens 28 to illuminate an alignment mark provided on a reticle 2. An image of the alignment mark is then formed on the sensor 30 through the objective lens 28 and the relay optical system 31. Further, through the illumination system relay optical system 33, the objective lens 28 and the projection lens 1, an alignment mark formed on the wafer 3 may be illuminated, and the mark may be imaged on the sensor 30, through the projection lens 1, the objective lens 28 and the relay optical system 33.

This enables observation of the wafer alignment mark. Alternatively, a further optical system may be disposed between the relay optical system 31 and the sensor 30, for example, if desired.

The phase restoration method using the above-described alignment optical system will now be explained. For the alignment measurement process, the alignment mark is illuminated usually with a condition of $0.2 \leq \sigma \leq 1.0$. To this end, in the alignment optical system shown in Figure 8, an interchangeable stop 32 is disposed between the illumination system relay optical system 33 and the beam splitter 29, such that the σ value can be changed between the alignment process and for execution of wavefront aberration measurement based on the phase restoration method. More specifically, for execution of the wavefront aberration measurement based on phase restoration, the stop is changed to provide $\sigma \leq 0.2$, to illuminate a pattern on the reticle. The intensity distribution of an image thereof is then measured by suing a light intensity measuring system 8, by which the wavefront aberration of the projection lens 1 can be calculated. Namely, as shown in Figure 8, the interchangeable stop 32 is provided inside the alignment optical system, so that the stop is interchanged between alignment measurement and wavefront measurement based on phase restoration, thereby to assure best illumination

states for them. With this structure, without use of any additional optical system, the phase restoration method can be executed very precisely, and the wavefront aberration of the projection lens 1 can be calculated conveniently and very precisely.

While in Figure 8 the light source 34 of the alignment optical system is made separate from the exposure light source, the same light source as the exposure light source may be used. Further, the light intensity detecting system 8 in the preceding embodiments may comprise a photosensor such as a CCD which may be mounted on the stage 4. Alternatively, an enlargement optical system (not shown) may be used to enlarge the intensity distribution and, after that, it may be measured by use of the photosensor.

A sixth embodiment of the present invention will be described. The structure of this embodiment is similar to that of the fifth embodiment shown in Figure 8.

This embodiment differs from the fifth embodiment in that, on the basis of the structure that the stage 4 can be moved two-dimensionally and precisely at a nanometer order, the light intensity detecting system 8 performs measurement of a light intensity distribution upon an image plane and adjacent thereto in accordance with a knife edge method. By using the knife edge method, the light

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intensity distribution can be measured very precisely without loading a heavy unit such as an enlargement optical system on the stage, as compared with a case where a photosensor is mounted directly on the stage 4. Alternatively, such an enlargement optical system and the knife edge method may be used in combination, to measure the light intensity distribution very precisely.

Figure 9 is a schematic view of a main portion of a projection exposure apparatus according to a seventh embodiment of the present invention. In Figure 9, elements corresponding to those of Figure 8 are denoted by like numerals.

In this embodiment, as shown in Figure 9, a reflecting portion (concave mirror portion) 9 is formed on a wafer stage 4. A pattern of a reticle 2 is imaged upon an intermediate image plane 36 by a projection lens 1. The intensity distribution of the image of the pattern is measured at the reticle 2 side, and the wavefront aberration of the projection lens 1 is measured in accordance with the phase restoration method. The measurement method will be described below, in greater detail.

A second light source 34 emits light of the same wavelength as the exposure wavelength. The light goes through an illumination system relay optical system 33, an interchangeable stop 32, a beam splitter

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29a and an objective lens 28, and it illuminates a pattern on the reticle 2 under an approximately coherent condition (σ is not greater than 0.2). While the pattern on the reticle 2 is imaged by the projection lens 1 at the same height as of the wafer 3, it is reflected by the mirror 9 formed on the wafer stage 4. Thus, the light goes again through the projection lens 1 and through a half mirror 7, it is imaged on the intermediate image plane 36. Here, the mirror 9 comprises a spherical surface mirror, and its curvature center is placed substantially at the same level as the wafer 3. The pattern of the reticle 2 being imaged on the intermediate image plane 36 after passing projection lens 1 twice, is then imaged on a sensor 30 while being magnified, through an enlargement optical system 35, a mirror 15, a beam splitter 29b, and a relay optical system 31. By moving the enlargement optical system 35 in a direction of an arrow in the drawing or by shifting the sensor 30, intensity distributions in an in-focus state and a defocus state can be measured.

With the structure described above, the measurement of the intensity distribution can be done with light passing the projection lens 1 twice. Thus, as compared with a method wherein light passes the projection lens only once, the measurement can be done with an aberration sensitivity twice higher than the

latter. Further, since the intensity distribution is imaged on the sensor 30 while being enlarged by means of the enlargement optical system 35, it can be measured with a good precision and, therefore, the wavefront aberration can be measured very precisely. Furthermore, only a mirror has to be formed on the wafer stage 4 and, conveniently, there is no necessity of mounting a heavy unit such as a sensor thereon for measurement of the light intensity distribution. Since this embodiment is arranged like the fifth embodiment of Figure 8 so that the phase restoration method is executed by using an alignment optical system, the sensor 30, relay optical system 31, light source 34, illumination system relay optical system 33 and the objective lens 28, for example, are used in common, in both optical systems. Therefore, the phase restoration method can be executed with minimum addition of optical elements.

While in this embodiment a spherical mirror is used as the mirror 9, a flat mirror having a reflection surface placed at the same level as the wafer surface may be used. In that occasion, among the wavefront aberration components, only symmetrical components such as spherical aberration and astigmatism, for example, can be measured at a twice sensitivity. This is because light beams passing through the projection lens in the forward path (from

reticle side to wafer side) and in the backward path (from wafer side to reticle side) are revolutionally parallel to each other with respect to a principal light ray, such that asymmetrical components are cancelled. Further, while a mirror having a concave surface is shown in Figure 9, it may comprise a convex surface mirror having a curvature center placed at substantially the same level as the wafer surface.

Figure 10 is a schematic view of a main portion of a projection exposure apparatus according to an eighth embodiment of the present invention. In Figure 10, elements corresponding to those of Figure 9 are denoted by like numerals.

In this embodiment, on the basis of a wavefront aberration as calculated in accordance with the phase restoration method, an aberration correcting optical system 12 (Figure 10) disposed inside a projection lens 1 is used to perform aberration correction, or the air spacing between lens elements of the projection lens 1 is adjusted. The aberration correcting optical system 12 may comprise an optical unit having a pair of aspherical surface optical elements of the same shape, being disposed so that their aspherical surfaces are opposed to each other, as disclosed in Japanese Laid-Open Patent Application, Laid-Open No. 242048/1998.

While in Figure 10 the aberration correction

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optical system 12 is disposed adjacent to a pupil plane of the projection lens 1, it may be disposed between the projection lens 1 and the wafer 3 or between the projection lens 1 and the reticle 2. Alternatively, plural elements may be disposed there.

In the embodiments described above, the wavefront aberration of the projection lens 1 is calculated on the basis of a focus plane (image plane) and one defocus plane. However, it can be calculated from intensity distributions of images at two different defocus planes, without using the focus plane (image plane). Further, the wavefront aberration can be calculated by using intensity distributions of images at three or more positions including a focus plane (image plane) and plural defocus planes. Furthermore, while an example of aberration correcting optical system comprising a pair of aspherical surface optical elements has been described, the invention is not limited to it. The aberration correction may be accomplished by moving plural lenses in a projection lens system, or by disposing one or more parallel flat plates between the projection lens and the wafer or between the projection lens and the reticle and by changing the angles of these parallel flat plates.

A projection exposure apparatus according to any one of the preceding embodiments may be used so

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that, after detection of the relative position between a mask and a wafer, a pattern on the mask surface is transferred to the wafer surface. Thereafter, the wafer is processed by a development treatment, for production of devices.

Between such exposure process and execution of phase restoration method, the illumination condition can be changed, such that, within the major assembly of the exposure apparatus, a wavefront aberration of the projection lens can be calculated very precisely in accordance with the phase restoration method. Particularly, for execution of the phase restoration method, an optical system may be added to the exposure illumination system or only a portion of the exposure illumination system is used so as to assure that a reticle is illuminated in an approximately coherent condition. Alternatively, the illumination optical system may be changed by replacing a portion thereof, for example. In this manner, the wavefront aberration can be measured very precisely.

For execution of phase restoration method, as described above, a second optical system different from the exposure illumination system may be used to illuminate a reticle in an approximately coherent state. The wavefront aberration of the projection lens can be calculated very precisely, also in such

case, in accordance with the phase restoration method and inside the major assembly of the exposure apparatus. The second optical system may comprise an alignment optical system. Thus, without any additional optical system, the wavefront aberration of the projection lens can be calculated very precisely in accordance with the phase restoration method and inside the major assembly of the exposure apparatus.

In accordance with the thus calculated wavefront aberration, an aberration correcting optical system, for example, disposed outside the projection lens, may be used to adjust the wavefront aberration of the projection lens. This enables an exposure process with small wavefront aberration.

While the foregoing embodiments have been described with reference to a step-and-repeat type projection exposure apparatus for manufacture of semiconductor devices, the invention is applicable also to a scanning exposure apparatus or an exposure apparatus for liquid crystal devices.

Next, an embodiment of a semiconductor device manufacturing method which uses a projection exposure apparatus according to any one of the preceding embodiments, will be explained.

Figure 10 is a flow chart of procedure for manufacture of microdevices such as semiconductor chips (e.g. ICs or LSIs), liquid crystal panels, CCDs,

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thin film magnetic heads or micro-machines, for example.

Step 1 is a design process for designing a circuit of a semiconductor device. Step 2 is a process for making a mask on the basis of the circuit pattern design. Step 3 is a process for preparing a wafer by using a material such as silicon. Step 4 is a wafer process (called a pre-process) wherein, by using the so prepared mask and wafer, circuits are practically formed on the wafer through lithography. Step 5 subsequent to this is an assembling step (called a post-process) wherein the wafer having been processed by step 4 is formed into semiconductor chips. This step includes an assembling (dicing and bonding) process and a packaging (chip sealing) process. Step 6 is an inspection step wherein operation check, durability check and so on for the semiconductor devices provided by step 5, are carried out. With these processes, semiconductor devices are completed and they are shipped (step 7).

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Figure 11 is a flow chart showing details of the wafer process.

Step 11 is an oxidation process for oxidizing the surface of a wafer. Step 12 is a CVD process for forming an insulating film on the wafer surface. Step 13 is an electrode forming process for forming electrodes upon the wafer by vapor deposition. Step

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14 is an ion implanting process for implanting ions to the wafer. Step 15 is a resist process for applying a resist (photosensitive material) to the wafer. Step 16 is an exposure process for printing, by exposure, the circuit pattern of the mask on the wafer through the exposure apparatus described above. Step 17 is a developing process for developing the exposed wafer. Step 18 is an etching process for removing portions other than the developed resist image. Step 19 is a resist separation process for separating the resist material remaining on the wafer after being subjected to the etching process. By repeating these processes, circuit patterns are superposedly formed on the wafer.

With these processes, high density microdevices can be manufactured.

In accordance with the embodiments described hereinbefore, a wavefront aberration of a projection optical system (projection lens) for projecting a mask pattern onto a wafer can be measured very precisely. Thus, with the present invention, a projection exposure apparatus or a device manufacturing method which facilitates production of large integration devices is accomplished.

While the invention has been described with reference to the structures disclosed herein, it is not confined to the details set forth and this application is intended to cover such modifications or

changes as may come within the purposes of the improvements or the scope of the following claims.

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